Effects of Environmental Variability on Long-Range Underwater Sound Propagation: Mode Processing of LOAPEX Measurements

Ilya A. Udovydchenkov
Applied Ocean Physics and Engineering Department, MS 9
Woods Hole Oceanographic Institution
Woods Hole, MA, 02543
phone: (508) 289-3680 fax: (508) 457-2194 email: ilya@whoi.edu

Grant Number: N00140810195

LONG-TERM GOALS

Our long-term scientific goal is to understand the basic physics of low-frequency long-range sound propagation in the ocean and the effects of environmental variability on signal stability and coherence. We seek to understand the fundamental limits to signal processing imposed by ocean variability to enable advanced signal processing techniques, including matched field processing and other adaptive array processing methods.

OBJECTIVES

The objectives of this work are: 1) to further develop the theory of modal group time spreads in realistic deep ocean environments; 2) to test the predictions of the theory using recent measurements, especially those made during the recent LOAPEX experiment; 3) to develop improved robust signal processing algorithms whose purpose is to extract estimates of modal group time spreads using a deficient receiving array; and 4) to test the extent to which the intensities of scattered LOAPEX arrivals can be predicted using the most accurate environmental information available. These topics are being investigated by I. Udovydchenkov as a WHOI postdoctoral fellow under the supervision of T. Duda in collaboration with NPAL investigators at RSMAS (especially M. Brown), APL/UW (especially J. Mercer, B. Howe and R. Andrew) and SIO (especially P. Worcester and M. Dzieciuch).

APPROACH

Our approach to addressing these objectives is centered on analysis of data recorded during the Long Range Ocean Acoustic Propagation Experiment (LOAPEX). Our work involves data analysis, testing and extending relevant theory as it relates to the LOAPEX measurements, and extensive propagation modeling. These efforts are directed towards quantifying acoustic fluctuations observed in the data and providing a theoretical basis for understanding these observations. The theoretical work relies heavily on the modal description of the acoustic field and exploitation of links between asymptotic mode theory and ray theory, i.e., aspects of ray-mode duality. A theory of modal group time spreads (a modal group arrival is a contribution to a transient wave field corresponding to a fixed mode number) has been previously developed [1]. Relevant theoretical extensions are being developed with emphasis on improving our understanding of the connection between environmental variability and wave field structure and stability.

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED
30 SEP 2008	**Annual**	**00-00-2008 to 00-00-2008**

4. TITLE AND SUBTITLE	5a. CONTRACT NUMBER
Effects Of Environmental Variability On Long-Range Underwater Sound Propagation: Mode Processing Of LOAPEX Measurements	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Woods Hole Oceanographic Institution,Applied Ocean Physics and Engineering Department, MS 9,Woods Hole,MA,02543**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES
code 1 only

14. ABSTRACT
Our long-term scientific goal is to understand the basic physics of low-frequency long-range sound propagation in the ocean and the effects of environmental variability on signal stability and coherence. We seek to understand the fundamental limits to signal processing imposed by ocean variability to enable advanced signal processing techniques, including matched field processing and other adaptive array processing methods.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			
unclassified	**unclassified**	**unclassified**	**Same as Report (SAR)**	**7**	

WORK COMPLETED

The first four items listed below are linked to analysis of the LOAPEX measurements. Item one is complete in the sense that the work has been published. The closely related work described in items two, three and four is currently being written up. That work has not yet been published, and in that sense is not yet complete, although most of the results that will be included in forthcoming publications have already been produced. Item five represents a new, and potentially very important, theoretical direction; some important preliminary results have been established.

1. Theory of modal group time spreads

A theory of modal group time spreads (a modal group arrival is a contribution to a transient wave field corresponding to a fixed mode number) has been developed [1]. It was shown in [1] that, in general, there are three contributions to modal group time spreads in realistic range-dependent environments: 1) the reciprocal bandwidth; 2) a deterministic dispersive contribution; and 3) a scattering-induced contribution. Theoretical expressions for all three contributions are given in that work.

2. Reduction of environmental mismatch

It has been shown that some of the observed disagreement between measured and simulated mode processed LOAPEX wave fields can be reduced by performing simulations in a reconstructed sound speed profile. The reconstruction (inversion) algorithm uses as input the travel times of modal group arrivals obtained from the mode processed LOAPEX measurements; the theoretical framework for this procedure was originally described by Munk and Wunsch [2]. The inversion algorithm has been implemented and it has been demonstrated that use of the inverted profile results in better agreement between measured and simulated wave fields. Figure 1 shows simulated and measured wave field intensities in the depth-time plane together with mode-processed results. That figure was constructed using the sound speed profile computed from CTD (conductivity-temperature-depth) measurements in the upper ocean matched with climatological data in deep ocean. Figure 2 is similar to Fig. 1, but it was produced with the reconstructed sound speed profile. Better agreement between measured and simulated mode-processed wave fields is observed using the reconstructed profile. This work was presented at the 11th NPAL workshop and is currently being written up.

3. Low mode number scattering of acoustic energy

It is shown in [1] that the scattering-induced contribution to a modal group time spread grows in range as r^(3/2). However, the derived expression for the scattering-induced contributions is inaccurate for modes with low mode numbers. Low mode numbers require special care because, unlike high mode numbers, energy in the gravest mode can be scattered only into higher mode numbers. A theoretical framework for treatment of near-axial scattering was presented in [4] and [5]; those results have been incorporated into our theoretical framework and the resulting theoretical predictions have been evaluated numerically. Figure 3 shows theoretical estimations of variances of travel time distributions (which are proportional to scattering-induced time spreads) normalized by r^(3/2). It is shown that in a LOAPEX-like environment the scattering-induced contribution for lowest mode numbers is reduced by a factor of approximately 2 due to this correction. This work is currently being written up.

4. Mode processing using a deficient receiving pseudo-array

The mode processing associated with the estimation of modal group arrivals requires that the wave field be measured on a vertical array that is both long and dense. In the LOAPEX experiment vertical receiving arrays on two separate moorings were used to collect data. These moorings were separated by approximately 5 km. Because of the horizontal separation between the moorings there are phase differences between data recorded on the two vertical arrays. However, for the purpose of estimating modal group time spreads in the LOAPEX experiment, we have shown that these errors are not so serious as to preclude mode processing when the two vertical arrays are combined to form a single pseudo-array. This work has been presented at NPAL workshops and is currently being written up.

5. Resonant scattering

Traditional theoretical treatments of the forward scattering of sound treat scattering events as uncorrelated events. Recently, we (I Rypina, M Brown and myself) have explored a conceptually very different theoretical framework in which scattering is controlled by resonant scattering. Resonances are excited between background rays, which are periodic in range, and periodic structures in the sound speed perturbation. Because modes can be associated with interfering up- and down-going rays, the resonant scattering approach is also applicable to the description of mode coupling. For a narrowband (in horizontal wave number) perturbation only a small number of resonances are excited, while internal-wave-induced perturbations, which contain many length scales, excite many resonances. A general expression for resonance widths has been derived [3]. This work was presented at the 11th NPAL workshop.

RESULTS

Considerable progress has been made on the development of a theory of acoustic scattering in long-range deep ocean propagation, especially the scattering of sound near the sound channel axis. Some of the LOAPEX data has been analyzed and generally good agreement between observations and theory has been observed. Also, we have significantly improved our understanding of the influence of the background sound speed structure on the resulting wave field fluctuations.

IMPACT/APPLICATIONS

The research described here has both scientific and operational applications. This work is contributing to an improved understanding of the basic physics of low-frequency long-range sound propagation in the ocean which is important in long-range tomographic systems, communication, and surveillance. Also, this knowledge contributes to an understanding of the limitations of advanced signal processing techniques, such as matched field processing.

TRANSITIONS

These results are being used to interpret the data collected during LOAPEX experiment. They also may be used for interpretation of previously collected data in the SLICE89, AET and SPICE04 experiments.

RELATED PROJECTS

The PI and collaborators listed above actively collaborate with many ONR-sponsored researchers who work on projects related to NPAL and participate in the NPAL workshops.

REFERENCES

[1] I. A. Udovydchenkov and M. G. Brown. Modal group time spreads in weakly range-dependent deep ocean environments. *J. Acoust. Soc. Am.*, 123:41-50, 2008.

[2] W. H. Munk and C. Wunsch. Ocean acoustic tomography: Rays and modes. *Rev. Geophys. Space Phys.*, 21:777-793, 1983.

[3] I. I. Rypina, M. G. Brown, F. J. Beron-Vera, H. Kocak, M. J. Olascoaga, and I. A. Udovydchenkov. Robust transport barriers resulting from strong Kolmogorov-Arnold-Moser stability. *Phys. Rev. Lett.*, 98:doi:10.1103/PhysRevLett,98,104102, 2007.

[4] A. L. Virovlyansky, A. Yu. Kazarova, and L. Ya. Lyubavin. Ray-based description of normal mode amplitudes in a range-dependent waveguide. *Wave motion*, 42:317-334, 2005.

[5] A. L. Virovlyansky, A. Yu. Kazarova, and L. Ya. Lyubavin. Statistical description of chaotic rays in a deep water acoustic waveguide. *J. Acoust. Soc. Am.*, 121:2542-2552, 2007.

PUBLICATIONS

[1] I. A. Udovydchenkov and M. G. Brown. Modal group time spreads in weakly range-dependent deep ocean environments. *J. Acoust. Soc. Am.*, 123:41-50, 2008. [published]

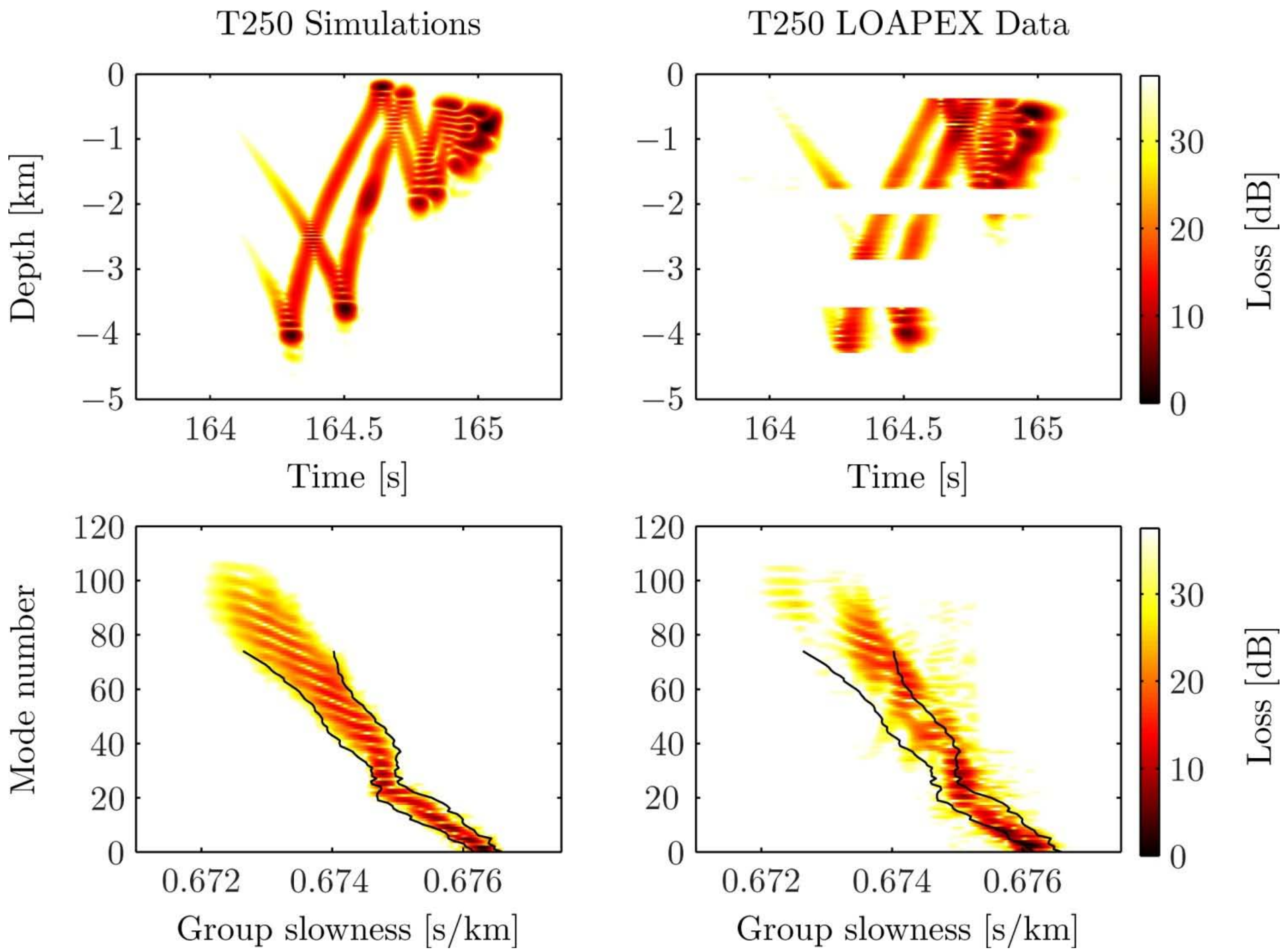

Figure 1. (upper panels) Simulated (left) and measured (right) LOAPEX wave fields in* (z,t) *at a range of approximately 250 km. The simulated wave field was constructed using an environment including an internal-wave-induced sound speed perturbation. (lower panels) The corresponding mode-processed wave fields in (m,S_g) where t = S_g r. Bounds on the predicted time spread are shown using solid lines. Note the mismatch between the mode processed data wave field and theoretical predictions.

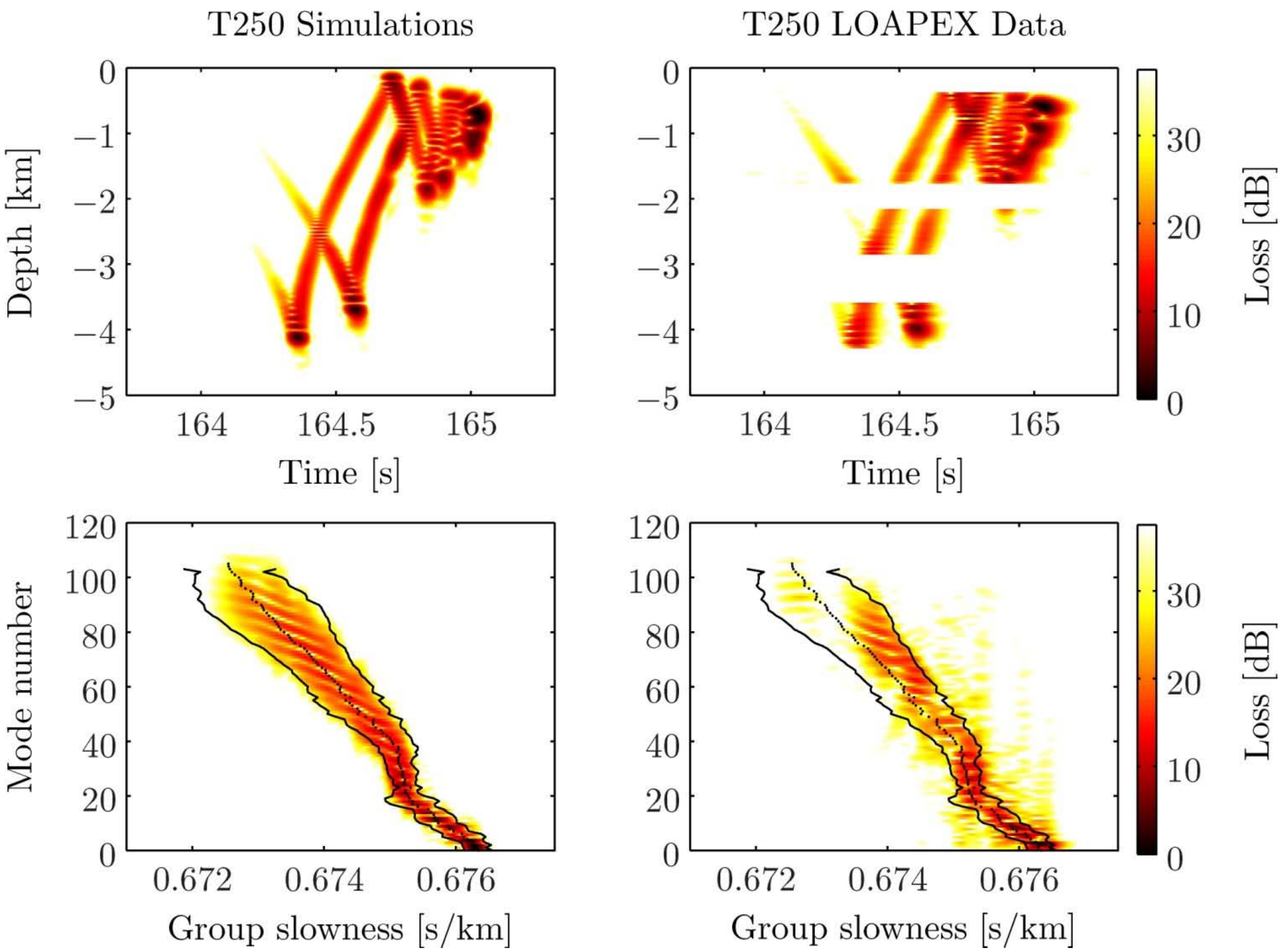

Figure 2. (upper panels) Simulated (left) and measured (right) LOAPEX wave fields in (z,t) at a range of approximately 250 km. The simulated wave field was constructed using a background environment reconstructed from measured modal group arrival times. An internal-wave-induced sound speed perturbation was superimposed on the background. (lower panels) The corresponding mode-processed wave fields in (m,S_g) where t = S_g r. Bounds on the predicted time spread are shown using solid lines. Note the improvement, relative to figure 1, between the mode processed data wave field and theoretical predictions.

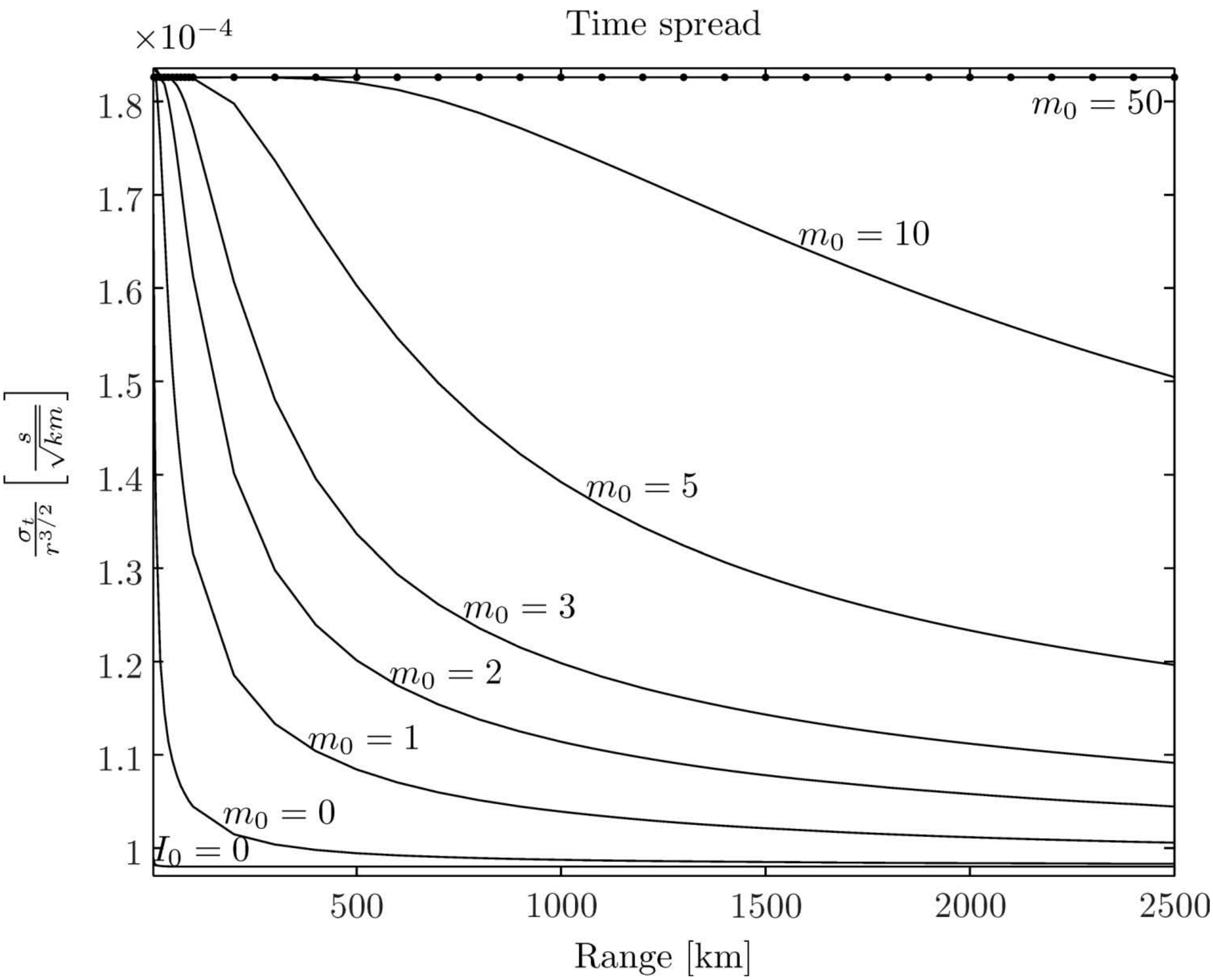

***Figure 3**. Theoretical estimates of variances of travel time distributions (which are proportional to scattering-induced modal group time spreads) normalized by r^(3/2). These estimates show how the range dependence of the scattering-induced contribution deviates from the r^(3/2)-law depending on the initial mode number. An asymptotic result for large m_0 is shown by dots.*